REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave Blank)

2. REPORT DATE
6 MAR 2003

3. REPORT TYPE AND DATES COVERED
Final, 1 JUL 2000 to ~~[illegible]~~ 15 Jan 03

4. TITLE AND SUBTITLE
Mechanical Diode Resonant Rectifying Actuator

5. FUNDING NUMBERS
Grant DAAD19-00-1-0422

6. AUTHOR(S)
George A. Lesieutre, Gary H. Koopmann, Eric M. Mockensturm

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
The Pennsylvania State University, Center for Acoustics and Vibration
157 Hammond Building
University Park, PA 16802

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U. S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
ARO Project No. 41346-EG
.1

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

The project goal is an efficient, conformable, high specific power actuator for use in agile high-speed DoD systems. Penn State pursued rotary motors based on the use of commercial roller clutches, while Virginia Tech demonstrated an efficient, regenerative drive system. The drive capacitors are roughly the same size as the motor piezos, thus bounding system size. Modeling indicated that the specific power of a bimorph-driven motor could be increased by a factor of 30 relative to initial SAMPSON technology; an 11X improvement was measured. The results indicated a limit of about 30 W/kg for such motors, inadequate to meet program goals, so stack-driven motors were subsequently pursued. Power output of 40 W and specific power of 30 W/kg were measured for the initial stack-driven motor. For such motors, Boeing and MPC suggested a focus on UCAVs, such as the X-45. This design was expected to provide a path to specific power in excess of 100 W/kg within a year. Achieving higher values will require diodes with smaller backlash; a number of devices were characterized as part of the development of a scaling model, and several reversible diodes were developed. Base-driven resonant drive was explored, which could enable impedance matching to a load, while avoiding stack tensile stress limits. A nonlinear transmission that increases power transfer in linear-to-rotary motion by 40% was also demonstrated.

14. SUBJECT TERMS
motor; piezoelectric motor; rotary motor; power density; specific power
stack-driven motor; high-frequency drive; resonant drive; impedance matching
motion amplification; mechanical diode; nonlinear transmission; efficiency

15. NUMBER OF PAGES
14

16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION ON THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev.2-89)
Prescribed by ANSI Std. 239-18
298-102

(1) Foreword (none)

(2) Table of Contents

(3) List of Appendices, Illustrations and Tables (none)

(4) Statement of the Problem Studied

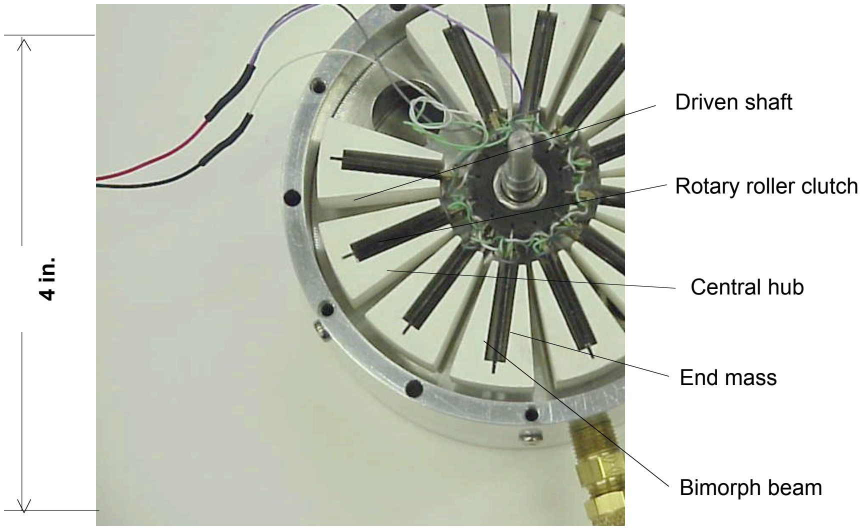
The DARPA Compact Hybrid Actuation Program (CHAP) addresses the development of compact motors and actuators that greatly exceed the power density and efficiency of current technology (hydraulic, EM, pneumatic) for use in future DoD systems. Such progress is enabled by the high potential power densities of smart materials, along with advances in power electronics and mechanical components. Building on previous DARPA investment via the SAMPSON program, a key feature of the technical approach is direct mechanical rectification and accumulation of high frequency resonant oscillation of a smart material drive element using "mechanical diodes." High power density is being pursued through advances in such diodes and in power electronics, using available electroceramic materials.

Compact actuators that exceed the power density and efficiency of current technology, while simultaneously offering improved geometric conformability, will dramatically improve the manueverability of DoD agile high-speed systems such as missiles and UCAVs. This enhanced maneuverability will enable higher-speed systems, reducing strike time and increasing accuracy. In addition, this technology will have applications to, and synergy with, other DoD systems and technology, such as radical shape-changing aerospace structures, robotic locomotion and articulation, more-electric vehicles, multi-functional structures, and energy harvesting.

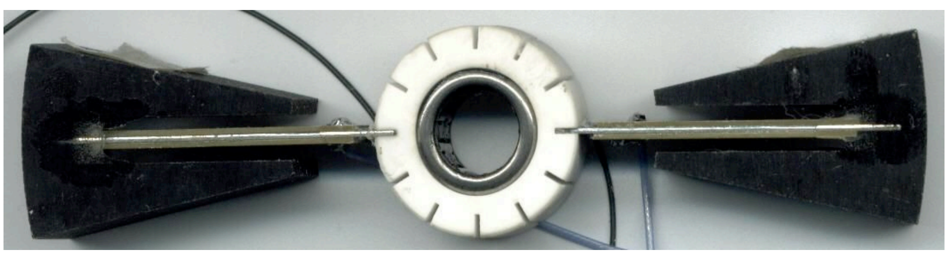
Significant technical progress was made from July 2000 to December 2001, the primary period of performance. Nominal additional progress was made with greatly reduced funding in the period from January to December 2002. This supplemental funding mainly served to support a graduate student while alternate research funding was sought.

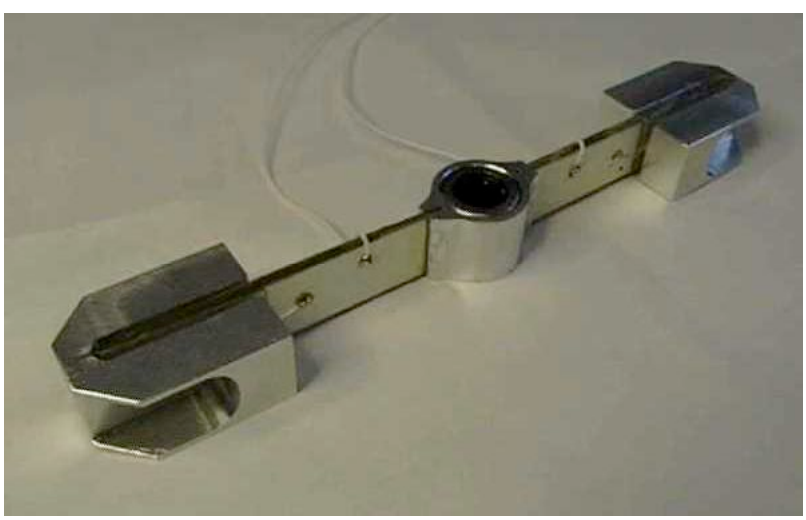
(5) Summary of the Most Important Results

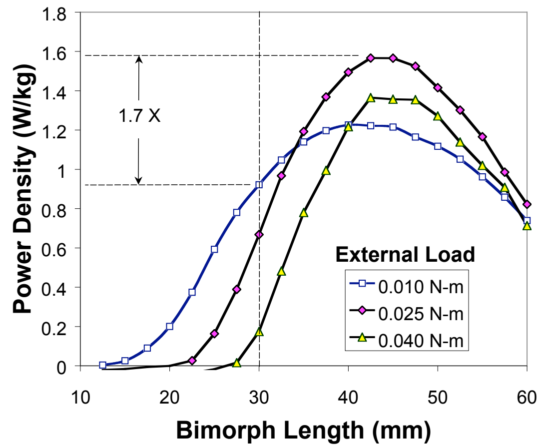
- This research started from the 11-arm DARPA SAMPSON piezoelectric motor, a proven concept.



- Penn State developed a dynamic model of 2-arm bimorph-driven rotary motor, and validated it by test; rotary diode characterization is an essential element of the model. The model was used as a basis for design optimization, predicting a 30X improvement in power density. To our surprise, the best size was somewhat larger than the baseline device that was already developed. This was due mainly to the backlash of the specific roller clutch used in the motor. See (Frank, J.E., G.H. Koopmann, W. Chen, E. Mockensturm, G.A. Lesieutre, and J.Y. Loverich, "Modeling And Design Optimization Of A Bimorph-Driven Rotary Motor," Journal of Intelligent Materials Systems and Structures, 2003) for additional details.

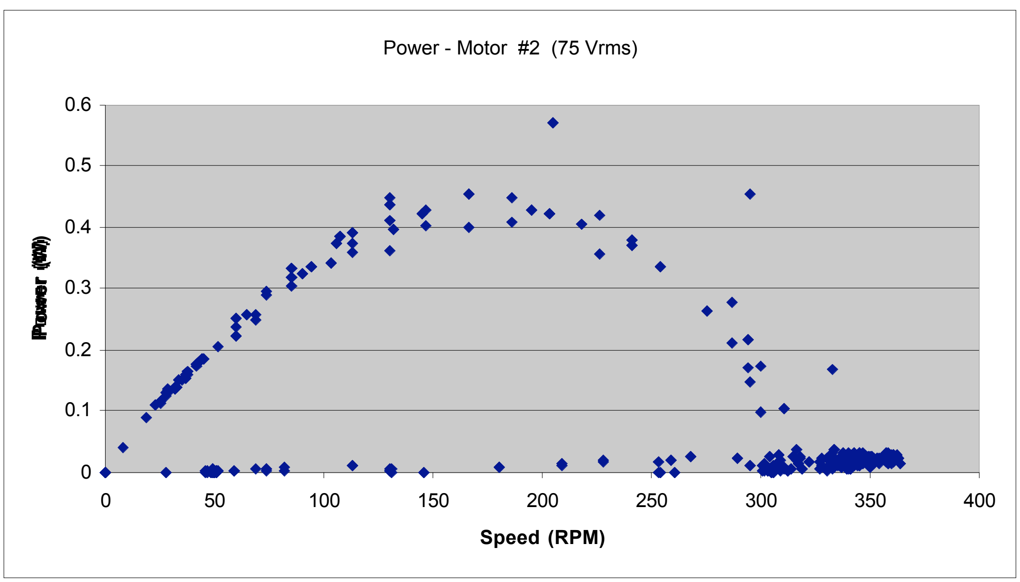




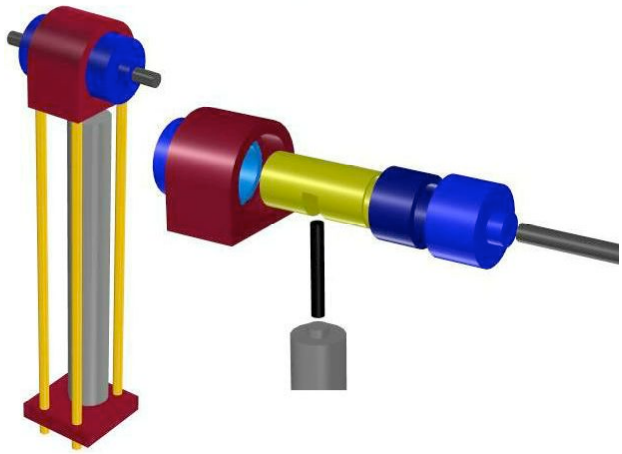


- Penn State built several near-optimal motors, and **measured an 11X improvement over the baseline SAMPSON 2-arm design**. One of the 2-arm motors had higher power output than the 11-arm SAMPSON motor.

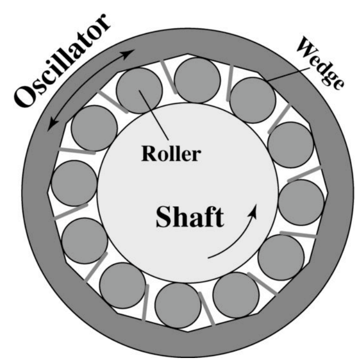
- Predictions and measurements indicated, however, that the best bimorph-driven motor built around a specific commercial roller clutch of a given size could achieve a maximum power density of only about 30 W/kg. This was deemed to be inadequate relative to program goals.



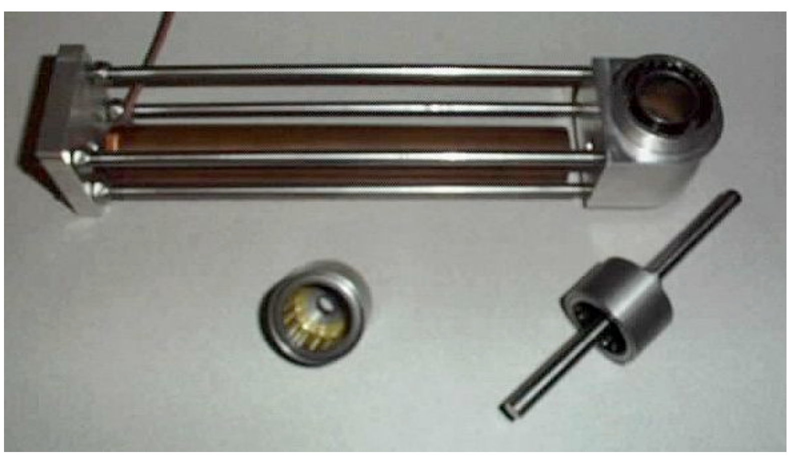
- Activity in the second half of CY 2001 focused on the **development of stack-driven motors**, both linear and rotary.

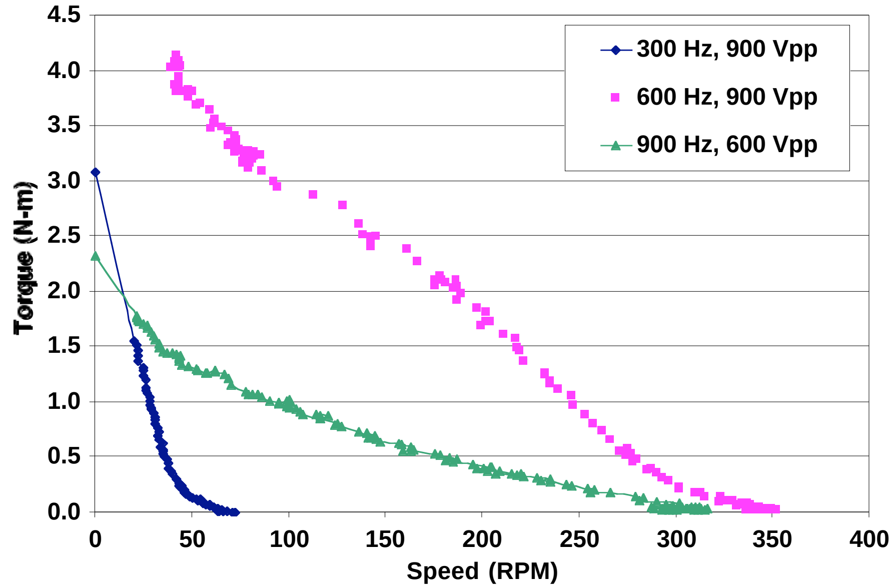


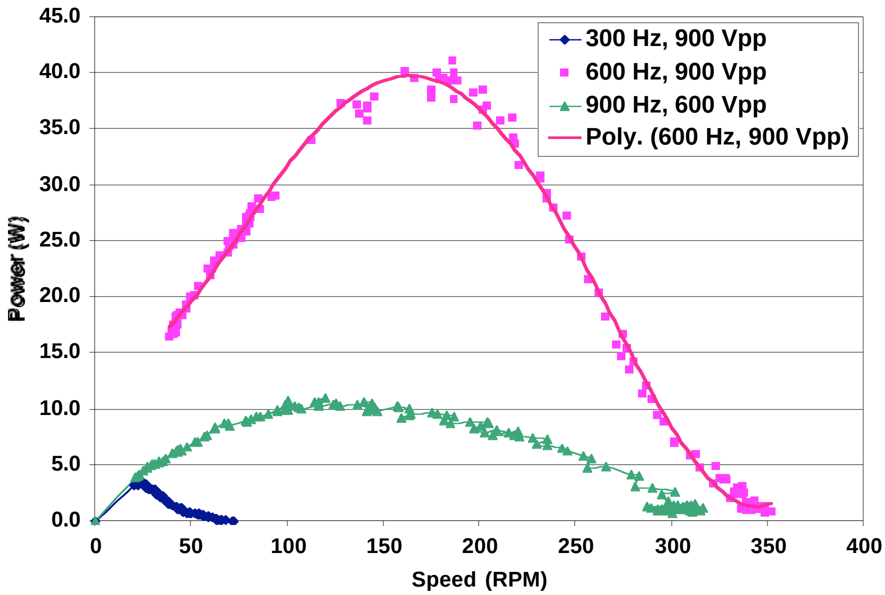
- 5 commercial roller clutches of various sizes were characterized. Larger roller clutches tend to have smaller angular backlash and compliance. An initial attempt to parameterize this data so that scale-dependent effects could be explored was not completely successful because the 5 commercial clutches are similar in many regards: the data is not information-rich.



- A relatively large stack-driven rotary motor was built to exploit this observation. **Power output of 40 W and specific power of 30 W/kg were measured for the initial stack-driven motor.** This design was expected to provide a path to specific powers in excess of 300 W/kg within a year. For additional details, see (Loverich, J.Y., Lesieutre, G.A., E.M. Mockensturm, G.H. Koopmann, and W. Chen, "A High-Power, Stack-Driven Rotary Piezoelectric Motor," Journal of Intelligent Materials Systems and Structures, 2003).







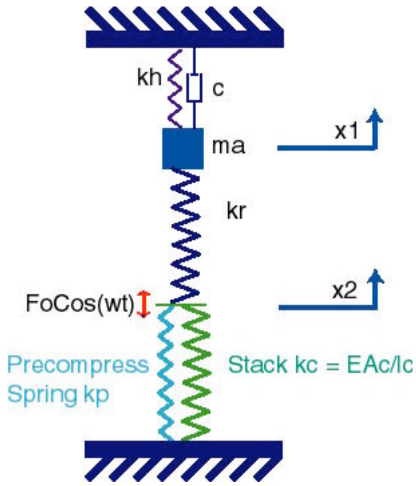
- First-order integrated models of motor electromechanical operation were developed and validated. These models were used to begin to address the following questions:

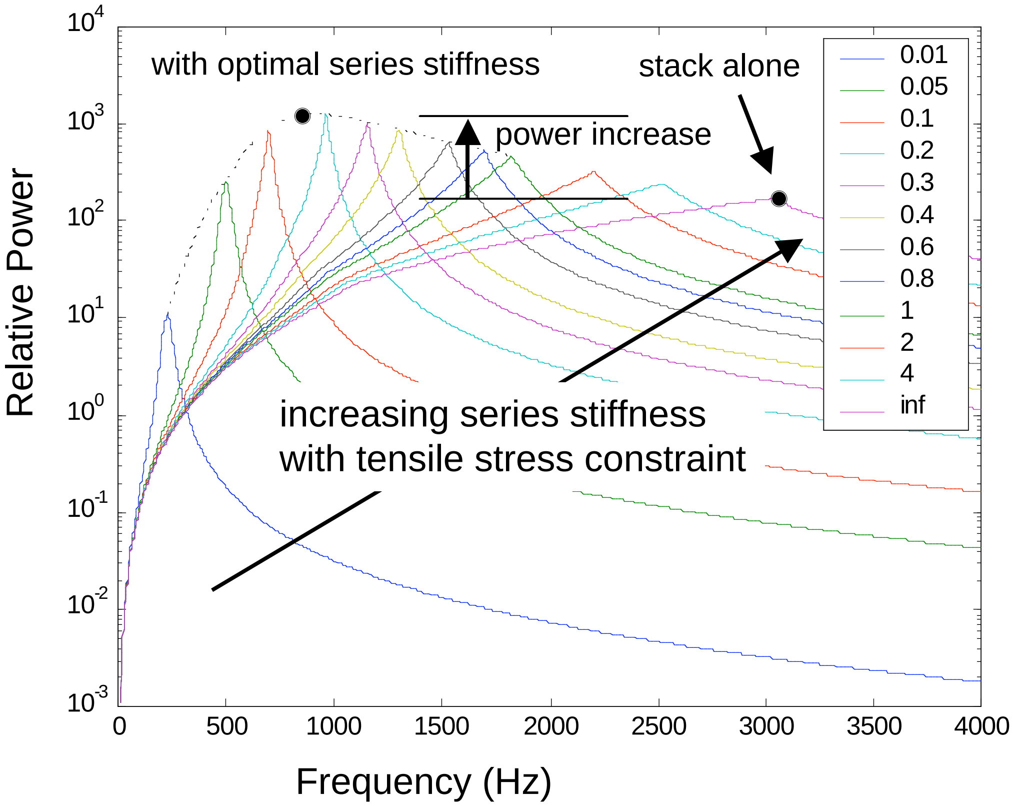
  What is the highest power density that can be obtained from a motor based on a commercial roller clutch?

  At what geometric scale is this power density obtained?

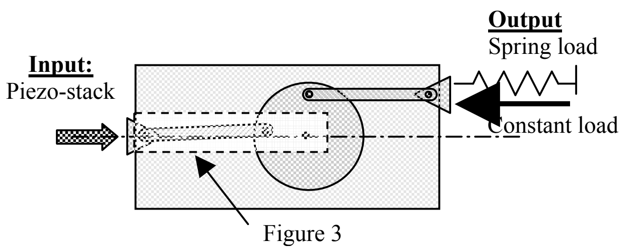
  If the power densities predicted are inadequate relative to application requirements, what modifications to the roller clutch would be required to achieve adequate levels?

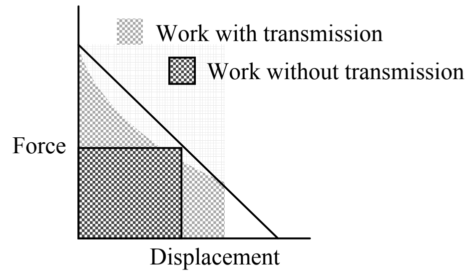
- Base-driven resonant drive concepts were also explored, but the optimal drive frequency was found to be relatively low and to depend strongly on the load magnitude. An important feature of resonant drive is that it is possible, by adjusting the frequency slightly, to “impedance-match” to a load for optimal power delivery. The main application, however, would seem to be for cases in which the piezo drive element has operating strain limits, perhaps associated with tensile stresses in ceramics.



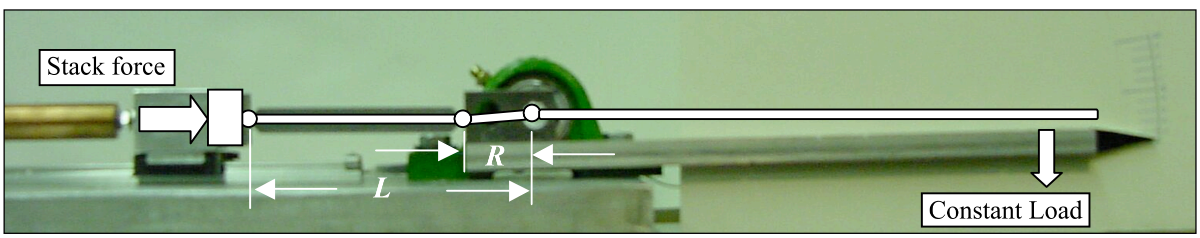


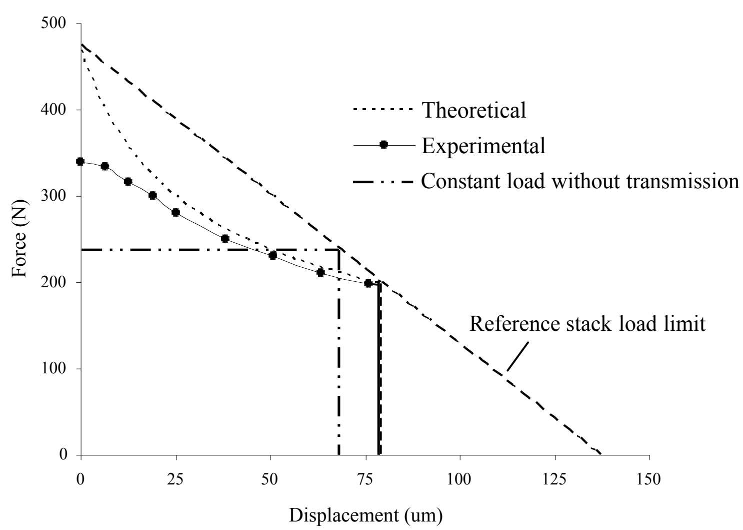
- A means to increase power transfer in linear (stack) –to-rotary (motor) motion was pursued and developed; this was the primary focus of activity in CY 2002 (a single student). It uses a nonlinear transmission that presents the stack with a stiff load at small displacements, and a softening load at larger displacements. This nonlinear transmission delivers approximately 40% more energy to a constant-torque load than a standard method, and nearly 100% to an elastic load.



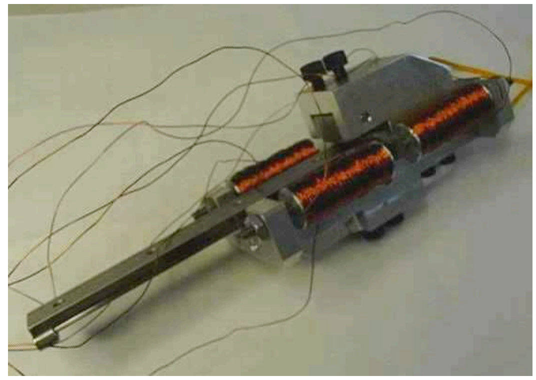


This approach was verified experimentally, with good agreement between measurement and theory. For additional details, see (Lesieutre, G.A., J.Y. Loverich, G.H. Koopmann, and E.M. Mockensturm, "A Nonlinear Transmission That Increases Piezo-Stack Work Output," Journal of Intelligent Materials Systems and Structures).



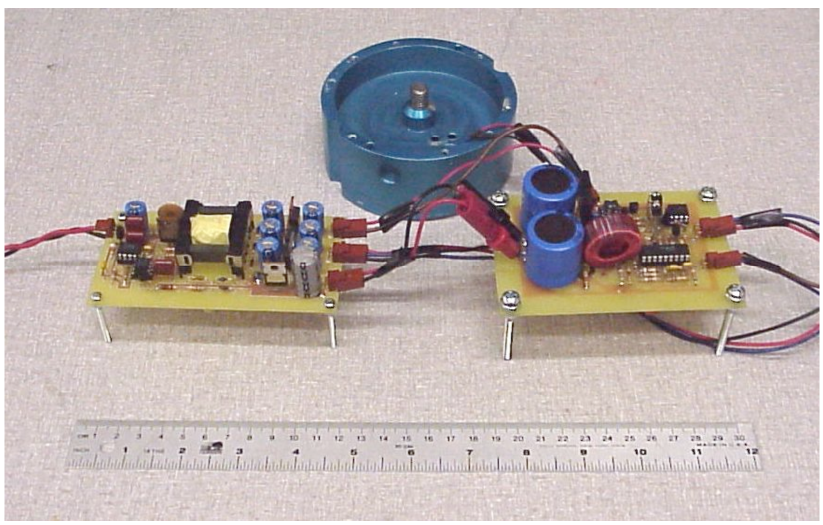


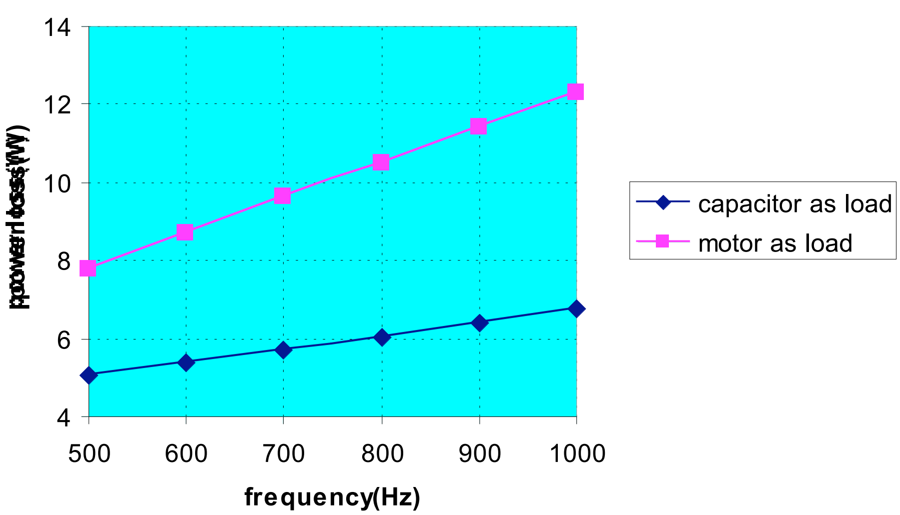
- A means to achieve reversible, 4-quadrant operation in a mechanical diode-based piezomotor is needed. That is, a motor should be able to deliver power to, or absorb power from, a load when moving in either direction. While important, this was a secondary focus of research in this program. Penn State developed several concepts for reversible linear diodes, and tested them. One is based on moving the locking rollers using magnetic force but, because of inertia, has some unavoidable finite response time.



This is a topic of continuing interest; some creative thinking is needed. Penn State developed several concepts for 4-quadrant rotary motors; all involve some kind of active mechanical diode. A main challenge is that such active mechanical diodes need to be able to operate at high frequency.

- **Virginia Tech researchers built an efficient drive amplifier for the 11-arm SAMPSON motor, and successfully demonstrated it.** They found that the capacitors needed inside the amplifier are roughly the same size as the piezos in the motors. This limits how compact the electronics can be.





- **Boeing identified several high-speed agile air vehicles whose missions would be enabled or significantly enhanced by a compact electric actuator. These include smart bombs (tail actuation, Small Smart Bomb Range Extension); a missile (fin control, Common Missile Program), and a UCAV (deformable control surface actuation).** The bimorph motor is a candidate for lattice fin control, while the larger stack-driven design is a candidate for the UCAV. There are applications for linear as well as rotary actuators. Volumetric conformability (the ability to have unusual form factors) is also an advantage.

Boeing and MPC established preliminary actuator requirements for application to a high speed agile vehicles.

One of the most promising applications is the Compact Kinetic Energy Missile, as its mission is enabled by the development compact actuation technology. Another promising application is the Small Diameter Bomb, the performance of which is greatly enhanced by compact actuation technology. One feature of the SDB application is that the actuator moments are relatively low, due to the use of lattice fins.

Application	Stall Force / Torque	Min Force/Torque under load, at rate	Rate under load	Total Deflection	Other
UCAV	11.1 kN	6.7 kN	11.4 **cm/sec**	10-15 cm	15 cm/sec no-load rate
JDAM	140 N-m	90 N-m	100deg/sec	50 deg	170 N-m/deg (k)
JASSM	170 N-m	110 N-m	83 deg/sec	50 deg	200 N-m/deg (k)
CKEM	TBD	TBD	TBD	TBD	TBD
SDB lattice fin	**3 N-m**	**2 N-m**	**100 deg/sec**	**40 deg**	**20 N-m/deg (k)**
MMT panel fin	**20 N-m**	**13 N-m**	**100 deg/sec**	**40 deg**	**20 N-m/deg (k)**

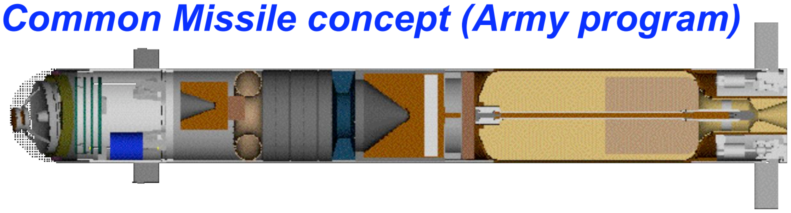
* Boeing design was not selected for production

UCAV = Uninhabited Combat Air Vehicle
CKEM = Compact Kinetic Energy Missile
JDAM = Joint Direct Attack Munition
SDB = Small Diameter Bomb (SSB/REX)
JASSM = Joint Air-to-Surface Standoff Missile
MMT = Miniature Munitions Technology

Small Diameter Bomb

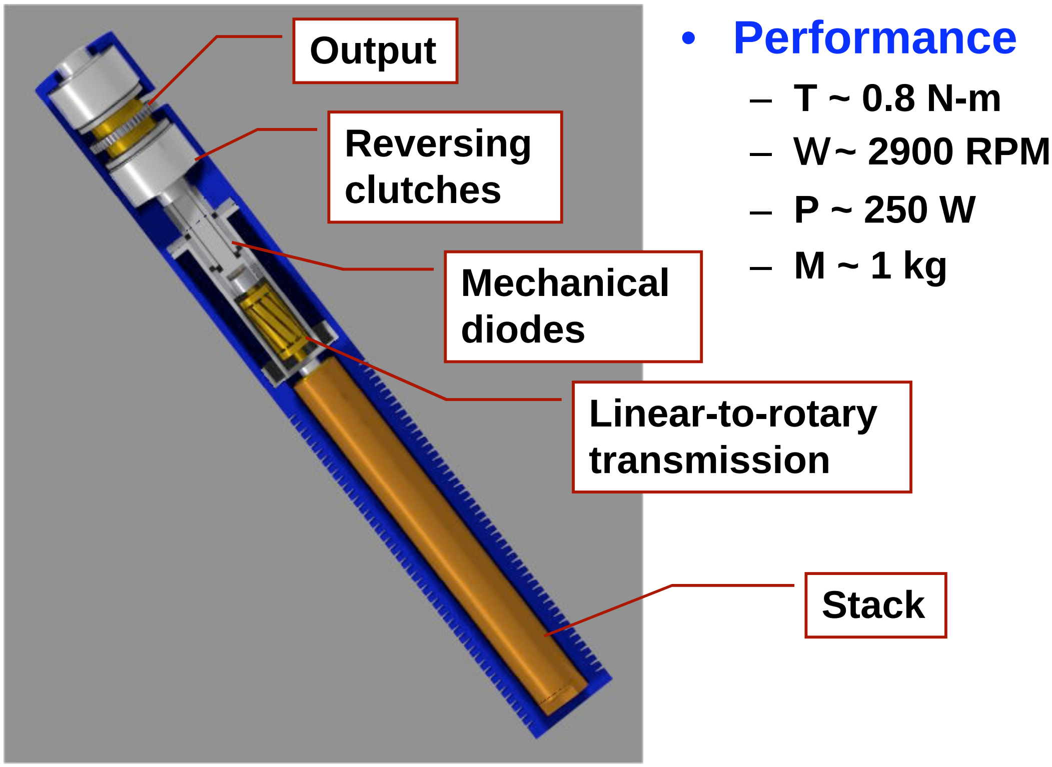
X-45 UCAV

Common Missile concept (Army program)



- MPC's experience as a motor manufacturer enabled them to bring critical realism to MEDIRRA motor designs.

- A proposal for Phase 2 continuation was submitted to DARPA. The focus was a compact, stack-driven actuator for UCAV control surfaces. Although the Phase 2 effort was not supported by DARPA, Penn State continues to explore the concept while seeking continuing research support.



Technology transfer

Boeing and MPC led the transition of this technology to aerospace applications. It would be somewhat premature to begin formal technology transfer from this project, although there were discussions with potential users of such technology, including the Army Common Missile program. MPC has some interest in trying to commercialize a version of the motor in its present state of development. With that approach, potential users might identify themselves and their applications, applications the technology development team is unaware of.

Penn State fielded inquiries from several companies about piezoelectric motor technology, among them, Dynetics. Dynetics makes a "lattice fin" for missile applications (recently featured in Aviation Week & Space Technology), and they were interested in high performance actuators that could fit in a confined space.

(6) Publications and Technical Reports

(a) Papers published in peer-reviewed journals

Frank, J.E., G.H. Koopmann, W. Chen, E. Mockensturm, G.A. Lesieutre, and J.Y. Loverich, "Modeling And Design Optimization Of A Bimorph-Driven Rotary Motor," Journal of Intelligent Materials Systems and Structures, 2003. (accepted)

Lesieutre, G.A., Hofmann, H., and Ottman, G., "Damping as a Result of Piezoelectric Energy Harvesting," Journal of Sound and Vibration, 2003. (accepted)

Ottman, G., Hofmann H., and Lesieutre, G.A., "Optimized Piezoelectric Energy Harvesting Circuit Using Step-Down Converter in Discontinuous Conduction Mode," IEEE Transactions on Power Electronics, 2002. (accepted)

Ottman, G., Bhatt, A., Hofmann H., and Lesieutre, G.A., "Adaptive Piezoelectric Energy Harvesting Circuit for Wireless Remote Power Supply," IEEE Transactions on Power Electronics, Vol. 17, No. 5, September 2002, pp. 669-676.

(b) Papers published in non-peer-reviewed journals or in conference proceedings

Lesieutre, G.A., J.Y. Loverich, G.H. Koopmann, and E.M. Mockensturm, "A Nonlinear Transmission That Increases Piezo-Stack Work Output," AIAA/ASME/AHS Adaptive Structures Conference, Norfolk, VA, April, 2003.

Lesieutre, G.A., Hofmann, H., and Ottman, G., "Damping as a Result of Piezoelectric Energy Harvesting," 2nd International Workshop on Damping Technologies -- Materials and Devices for the Next Decade, European Office of the U.S. Army Research Office (ERO), Cape Town, South Africa. March 24-26, 2003.

Loverich, J., G.A. Lesieutre, and G.H. Koopmann, "Enhancement Of Mechanical Work Output Of A Piezo-Stack Using A Non-Linear Motion Transmission Mechanism," 13th International Conference on Adaptive Structures Technology, Berlin, Germany, October 11-13, 2002.

Lesieutre, G.A., Hofmann, H., and Ottman, G., "Damping as a Result of Piezoelectric Energy Harvesting," 13th International Conference on Adaptive Structures Technology, Berlin, Germany, October 11-13, 2002. .

Loverich, J., G.A. Lesieutre, and G.H. Koopmann, "A New Mechanically-Ratcheting Piezoelectric Motor for High Power Applications," 2002 U.S. Navy Workshop on Acoustic Transduction Materials and Devices, Baltimore, MD, May 14, 2002.

Mockensturm, E.M., G.H. Koopmann, J. Frank, G.A. Lesieutre, "Design and Optimization of a Bimorph Actuator Drive with a One-Way Clutch," AIAA Adaptive Structures Forum, Denver, CO, April, 2002.

Lesieutre, G.A., Ottman, G., Bhatt, A., Hofmann H., "Structural Damping as a Result of Piezoelectric Energy Harvesting," annual meeting of the Acoustical Society of America, Ft. Lauderdale, December, 2001. (invited)

Lesieutre, G.A., G.H. Koopmann, E.M. Mockensturm, J. Loverich, D. Ericson, "Mechanically-Ratcheting Piezoelectric Motors," 12th International Conference on Adaptive Structures Technology, College Park, MD, October 15, 2001.

Mockensturm, E.M., J.E. Frank, G.H. Koopmann, and G.A.Lesieutre, "Optimization Of A Resonant Bimorph Actuator Drive," Proceedings of DETC 01: ASME 2001 Design Engineering Technical Conferences, Pittsburgh, September 9-12, 2001.

Lesieutre, G.A., G.H. Koopmann, E.M. Mockensturm, J.E. Frank, and W. Chen, "Mechanical Diode Based, High-Torque Piezoelectric Rotary Motor," AIAA Adaptive Structures Forum, Seattle, WA, April, 2001.

Lesieutre, G.A., Koopmann, G.H., Mockensturm, E.M., Frank, J.B., Chen, W., "Resonant Bimorph Driven, High-Torque Piezoelectric Rotary Motor," SPIE Smart Structures and Materials Conference, Newport Beach, CA, March, 2001.

E. M. Mockensturm, J. Jiang, G.H. Koopmann, G.A. Lesieutre, "Modeling And Simulation Of A Resonant Bimorph Actuator Drive," SPIE Smart Structures and Materials Conference, Newport Beach, CA, March, 2001.

(c) Papers presented at meetings, but not published in conference proceedings

(d) Manuscripts submitted, but not yet published

Lesieutre, G.A., J.Y. Loverich, G.H. Koopmann, and E.M. Mockensturm, "Increasing Mechanical Work Output Of an Active Material using A Non-Linear Motion Transmission Mechanism," Journal of Intelligent Materials Systems and Structures, 2003. (submitted)

Lesieutre, G.A., J.E. Frank, E.M. Mockensturm, W. Chen, and G.H. Koopmann, "Scaling of Specific Power in Piezoelectrically-Driven Rotary Motors," Journal of Intelligent Materials Systems and Structures, 2002. (submitted)

Loverich, J.Y., Lesieutre, G.A., E.M. Mockensturm, G.H. Koopmann, and W. Chen, "A High-Power, Stack-Driven Rotary Piezoelectric Motor," Journal of Intelligent Materials Systems and Structures, 2003. (in preparation)

(e) Technical reports submitted to ARO

(7) Participating Scientific Personnel and Awards

Penn State University
George A. Lesieutre, Professor of Aerospace Engineering, **AIAA Zarem Educator Award, January 2001; 2001 ASME/Boeing Structures and Materials Award**, for the Best Paper of the 2000 AIAA SDM Conference; **Chair of the AIAA Adaptive Structures Technical Committee.**

Gary H. Koopmann, Distinguished Professor of Mechanical Engineering, **ASME Per Brüel Gold Medal, 2001.**

Eric Mockensturm, Assistant Professor of Mechanical Engineering, **NSF CAREER Award, January 2002.**

Weiching Chen, Laboratory Director, Center for Acoustics and Vibration

Jacob Loverich, Ph.D. candidate, Mechanical Engineering, **NSF Japan Fellowship, January 2002; World University Network Fellowship, 2003.**

Jeremy Frank; **completed Ph.D. in Mechanical Engineering, March 2001.**

Jie Jiang, Ph.D. candidate, Mechanical Engineering

David Ericson, **completed M.S. in Mechanical Engineering, May, 2002.**

Deepak Ramrakhyani, Ph.D. candidate, Aerospace Engineering

Boeing Phantom Works
Edward V. White, Technology Leader, Smart Structures and Systems
Jay K. Burnham, Engineer, Smart Structures and Systems

MPC Products Corp.
Robert Drwal, VP R&D
Craig Scott, VP Engineering
Darrin Kopala, VP Aerospace Products
Pete Perrine, Sales Director
Eric Lowalker, R&D Engineer
Chris Doell, Product Engineer

Virginia Tech
Doug Lindner, Associate Professor, Electrical Engineering
Molly Zhu, Ph.D. student, Electrical Engineering

(8) Report of Inventions (by title only) (none)

(9) Bibliography (none)

(10) Appendixes (none)